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Chapter 3

Source Mechanism and Wave Propagation Arrays

3.1 INTRODUCTION

The strong earthquake ground motion experienced at a given site can be considered to be a space-time convolution of the earthquake source function with the path effect and the effect of local site conditions. This chapter deals with the design of arrays to measure source and path effects for strong ground motion.

For a large earthquake, which generates strong ground motion of crucial engineering interest, the rupture process can extend hundreds of km and may last several minutes. Both the spatial and temporal behavior of such earthquakes are at present poorly understood. Although there are hundreds of seismic stations, many of which have been in operation for decades, only a few have recorded the complete source signature in the immediate neighborhood of the faulting associated with a large ($M \geq 7$) earthquake. Many of the existing seismic stations are operated at high gain with limited dynamic range, and therefore if near the epicenter of a large earthquake will undoubtedly be saturated immediately after the first wave arrival.

In the worldwide earthquake belts there are less than a thousand strong-motion stations that have adequate timing and response to give onscale records close to large earthquakes. Most of these strong-motion stations are located in California, although California is far from being the most seismically active area in the world.

A combined analysis of the worldwide strong-motion instrument distribution and the recurrence rate of large earthquakes shows that there is a great need for systematic deployment of relatively extensive strong-motion arrays in the most seismically active areas of the world. This deployment is necessary for the engineering profession to gain adequate knowledge of various types of sources of large earthquakes within a reasonable period of time, say less than 10 years.

While the source function is one factor influencing the ground motion at a site, the material properties of the upper part of the crust, variations in layer thickness, surface topography and local site conditions combine to continuously shape the strong ground motion as waves propagate from the source. The present inadequate distribution of strong-motion instruments makes difficult if not impossible a systematic study of this path effect. This, in turn, makes it virtually impossible for design engineers to predict accurately the ground motion of a site even for a known earthquake source.

The accurate prediction of strong ground motions at various engineering sites could result in an enormous reduction of design and construction costs. One can easily visualize that the savings resulting from strong-motion array deployment might be orders of magnitude greater than its cost.

Although the precise mechanism by which strong seismic waves are generated and transmitted to a site is quite complex, it is possible to identify three principal source types:

1) Strike-slip fault with fault length as long as 1000 km

2) Low-angle subduction thrust fault with fault length as long as 1000 km

3) Dip-slip fault (thrust or normal) with moderate fault length (~50 km).

It is also possible to identify two main types of path structures:

1) Uniform layered crust with and without waveguide effects

2) Basement-Sedimentation Basin transition with significant, relatively simple lateral heterogeneities as boundaries of sedimentary basins, contacts of different upper crustal materials, deep waveguides and other more complex three-dimensional heterogeneities.

In this chapter strong-motion array designs are presented which are intended to provide data close to large earthquakes. Although the new data by themselves would fill critical gaps in the existing strong-motion data base, one must realize the much greater potential of these data. If, through detailed correlation analysis, some regularity can be found that empirically relates the observed strong ground motion to the path and the source, the results can be generalized to the prediction of strong ground motions at other sites under different conditions. The above data base can also be integrated with recent advances in near-source numerical and analytical calculations, thereby allowing the possibility of a more quantitative functional relationship between the source and path properties and the strong motion at a site. This will further increase the usefulness of the output of the proposed strong-motion instrumentation arrays.

It is realized that even for the most widely chosen sites, there is a great uncertainty of recording large earthquakes with fixed arrays within a few tens of years. To remedy this situation, it is recommended that at least one mobile array be created. This mobile array would consist of approximately 50 instruments, operated by a trained staff prepared to go into areas of the world immediately after a large earthquake. Such an "aftershock chasing" program should allow the recording of near-source strong motion of numerous M = 5 events, many M = 6 events, and perhaps one or two M = 7 events within a few years. This mobile array could also be deployed in an area where a major earthquake is anticipated.

3.2 GENERAL CONSIDERATIONS

Source Effects

At present, what is known about the dynamics of the source of an earthquake has come from observations of relatively long period waves (5-300 sec) recorded at great distances from the fault. These data provide average properties of the source, such as the fault orientation, the approximate rupture velocity, the average slip across the fault, and the total duration of the rupture process. In order to obtain information of relevance to engineers, a detailed knowledge of the short wavelength, high frequency nature of the source is needed. This can only be obtained by recording in the near-source region. The teleseismic recordings do indicate, however, that the fault slip in a large event is not a simple, smooth process, although the resolution of these details using teleseismic data is limited to tens of kilometers. It is most likely that smaller scale heterogeneities, which will be crucial for the radiation of high frequency waves also exist. Ideally, the source is described by the spatial and temporal dependence of the fault slip. The arrays proposed herein have been designed to provide as much detail as is practical about this dependence.

The arrays have been designed to answer questions such as: How fast does the fault rupture grow, how smooth is this growth, how does the acceleration vary as a function of azimuth, and is the ground motion maximum at the fault or at some distance away from the fault? Two general types of arrays are proposed for source studies. These are differentiated by their time period of operation and flexibility. One is the permanent array to be installed in areas where magnitude 7 to 8 earthquakes are expected. The spacing and the geometric patterns of such arrays are designed to resolve as much of the source details as is possible with a surface installation (unless there are many sensors at depths of several kilometers, a very expensive proposition, the gain over surface arrays is not significant). Such arrays are designed also to minimize the influence of local effects.

The other type of array for source study is a smaller mobile array that can be moved into the meizoseismal area of a major earthquake (magnitude 7 to 8) within a few days after the event. While the permanent array may have to stay in an area for many years, the mobile array can record many magnitude 6-7 aftershocks in the same time period. Thus the information return can be very high.

Path Effects

Small earthquakes and theoretical studies for impulsive inputs show that geological structure along the path and local site can introduce considerable complexities that depend on distance and period -- e.g., dispersion and interference of body and surface waves, attenuation, reverberation, focusing and defocusing, wave conversions, etc.

At present, few strong-motion stations have been placed with the direct objective of studying path effects. Also, analytical studies are limited, by and large, to relatively simple geologic structures. There is a need to understand the effects of different types of paths, e.g., a uniform crust, a large sedimentary basin, etc., and the transition effects when waves cross the boundary between different types of geologic structure. The degree of complexity that must be built into theoretical models should also be determined. Other factors such as scattering and lateral changes in waveguide properties could all contribute to the total path effects, especially at high frequencies.

The permanent network designed for source studies can be used to study path effects in the vicinity (within 20 km) of the fault, but it will be necessary to augment this network by additional instruments extending linearly to distances up to ~100 km away from the faults for significant path effects study. When there is a local effect array in the area, the extension could then provide continuous complimentary coverage to that array.

Much of the path effect study can be performed with the proposed mobile array. With earthquakes of magnitude 4 to 7, occurring either as background seismicity or aftershocks, it is possible to study many different paths and accumulate data rapidly. Although it is anticipated that nonlinear path effects are small, this array can supply data for a study of such effects.

Impulse Response Methods

For a particular site and for the case in which the possible source regions are known, it may be possible to use small earthquakes with foci distributed over the expected source regions to study path and local effects. The response for the smaller earthquakes can be used as impulse response or Green functions which may be convolved with a suitable source function for the larger earthquake, thus permitting the prediction of strong motion at the site including automatically the path and local site effects. This technique is particularly promising in situations where the path or local effects are too complex and thus difficult to represent by analytical models. Application of the technique is based on the assumption of small nonlinear local effects, although its use may be extended by appropriate correction for local nonlinear effects.

3.3 RECOMMENDED ARRAYS

To meet the above-stated data acquisition requirements and keeping in mind the limitations on available resources, an optimized array design approach is formulated. It is believed that the recommended instrument deployment will generate within a short period of time a sufficient strong-motion data base which should give engineers adequate information to evaluate the source and path effects on strong earthquake ground motion at a given site.

Permanent Source Mechanism and Path Effect Arrays

It is recommended that three types of faults be instrumented:

1. Strike-slip fault having linear dimension of many hundreds of km and capable of generating M = 8 earthquakes. A comb-shaped array is recommended consisting of approximately 100 to 200 instruments with an average spacing of about 10 km (Fig. 3.1).

2. Subduction thrust fault having linear dimension of many hundreds of km and capable of generating M = 8 earthquakes. Geographical location of the surface fault trace for this fault type (off-shore) only permits the hanging block of the fault to be instrumented. Deployment of a linear or two-dimensional narrow band array (Fig. 3.2) consisting of approximately 50 to 150 instruments of 20 km average spacing is recommended.

3. Dip-slip fault having relatively smaller linear dimensions of about 50 km and capable of generating earthquakes up to M = 7. Faults of this type are numerous and often located close to or directly under metropolitan areas, thereby posing high hazard to structures. A two-dimensional array of 2 to 10 km spacing is recommended (Fig. 3.3). One hundred instruments would be necessary to implement this array.

Mobile Array Laboratory

With the permanent arrays, there is a distinct possibility that this project may not yield the range of observations needed for a long period of time. A mobile array with about 50 portable instruments is recommended to record the strong ground motion generated by large aftershocks (M = 6 or 7) following the occurrence of giant earthquakes (M = 7 or 8). A careful preplanning of the logistics is necessary to allow sufficiently rapid deployment of this mobile array to record the largest aftershocks. The smaller aftershocks, which usually continue for years, and the magnitude 6-7 aftershocks can provide significant source information.

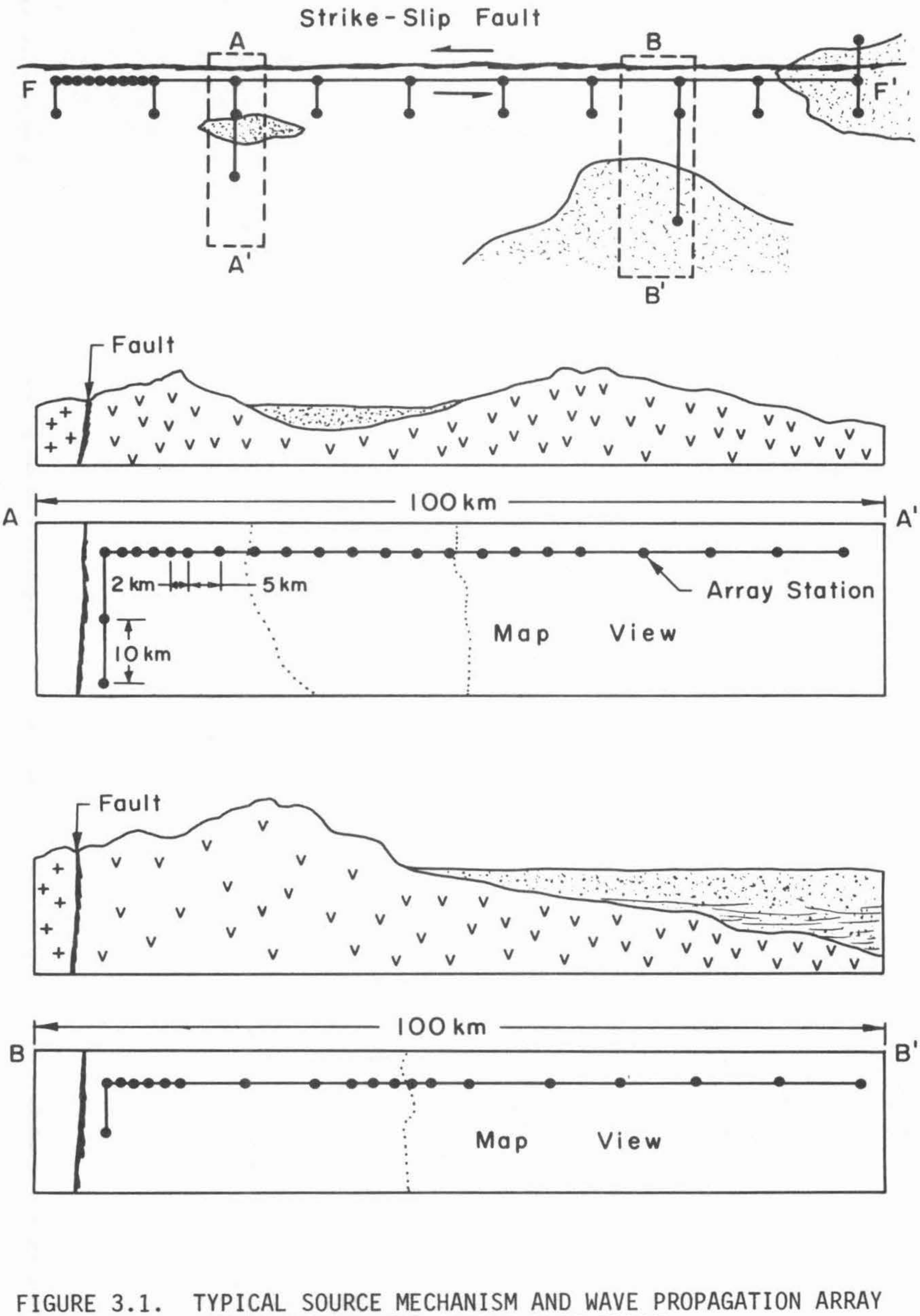

FIGURE 3.1. TYPICAL SOURCE MECHANISM AND WAVE PROPAGATION ARRAY CONFIGURATION FOR STRIKE-SLIP FAULT

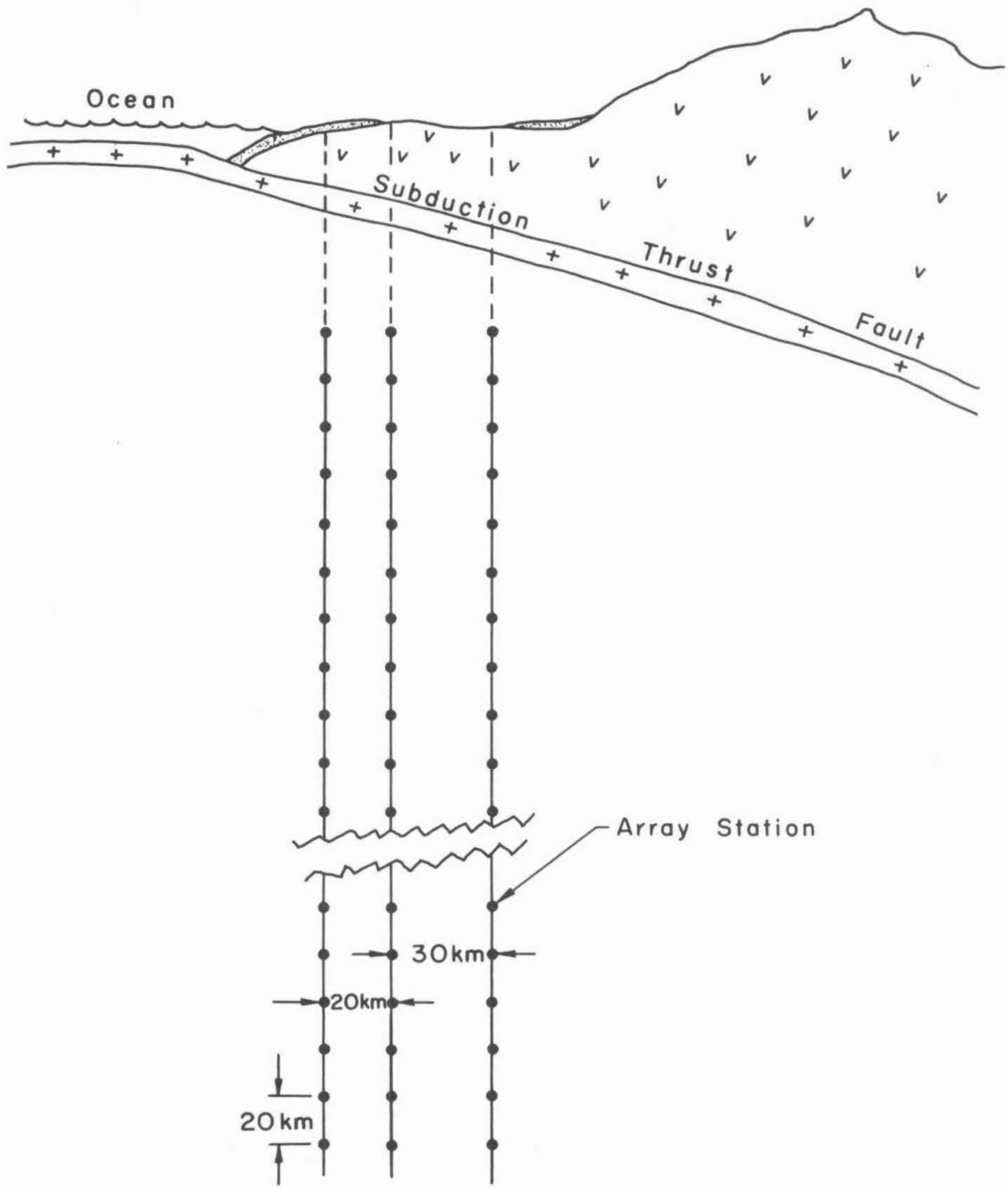

FIGURE 3.2. TYPICAL SOURCE MECHANISM AND WAVE PROPAGATION ARRAY FOR SUBDUCTION THRUST FAULT

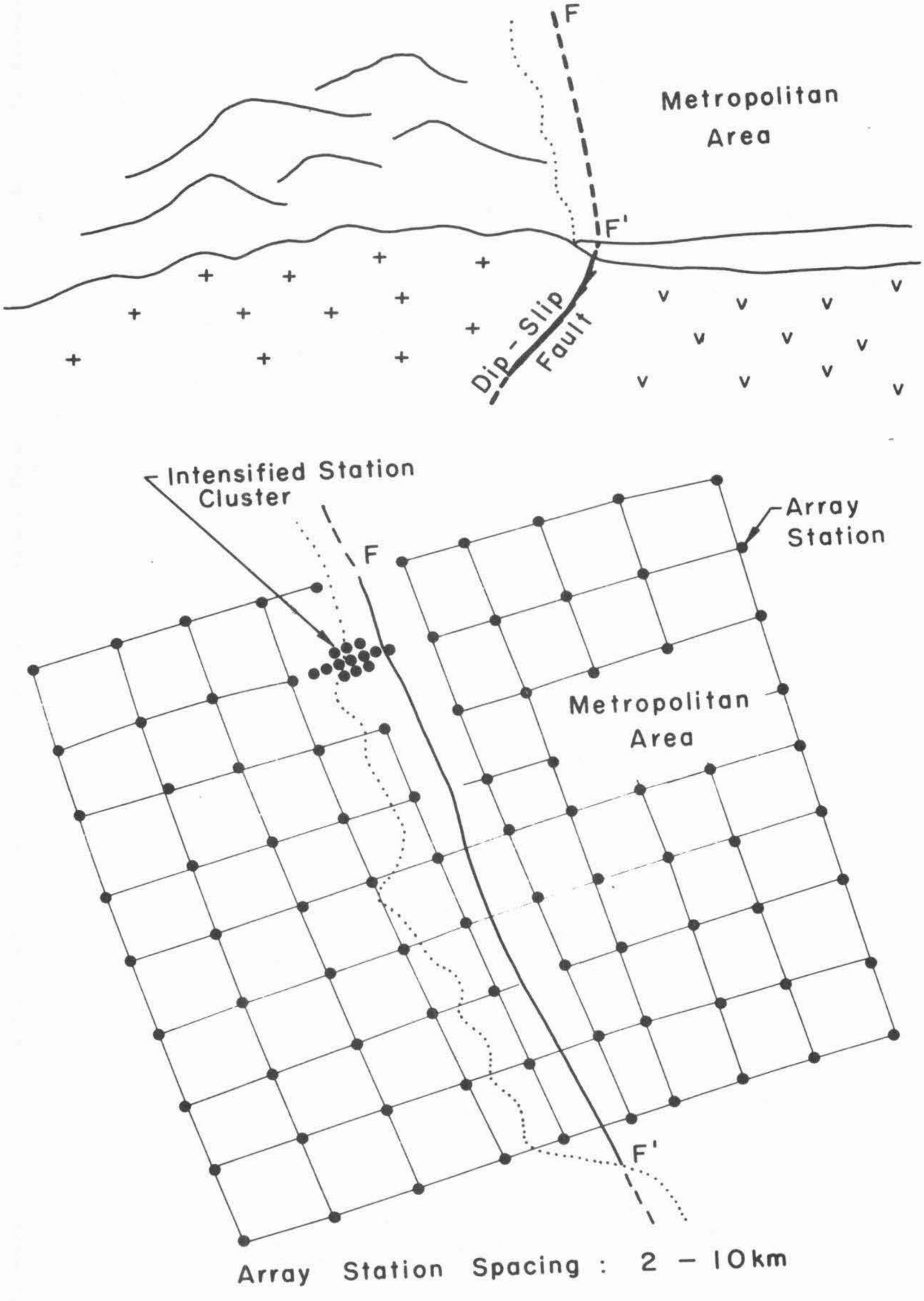

FIGURE 3.3. TYPICAL SOURCE MECHANISM AND WAVE PROPAGATION ARRAY CONFIGURATION FOR DIP-SLIP FAULT

3.4 DESIGNS FOR PERMANENT SOURCE MECHANISM AND PATH EFFECTS ARRAYS

Source Mechanism Studies

Most basically, it is desired to study the source function and seismic radiation of earthquakes, that is, how the slip of a fault and the resulting radiation vary in space and time. In particular it is desired to know how this source function and radiation vary with the geologic and tectonic conditions and the magnitude, mechanism and depth of the earthquake.

Such knowledge will, for a given location, allow the prediction of the range of possible source functions. This can be used as input to a local site effect study. An example of a particular result sought is the azimuthal variability in radiated energy that can be expected from source orientation and interference patterns produced by rupture along a fault. In order to estimate this it is necessary to observe a given event at a number of different azimuths. Another important piece of information is to know the conditions under which there are multiple events in a large rupture process. Such a rupture process produces proportionately greater high frequencies than a smooth rupture.

The principles that have been followed in the design of source mechanism arrays are:

1) Every effort has been made to minimize local and propagation path effects relative to source effects by placing (when possible) the station on similar competent rock sites near the potential fault and the recording site. It is impossible to completely eliminate local and propagation path effects, or even to make these effects the same at all our recording sites. Therefore, to provide a means to check the magnitude of these effects on source mechanism data, recording sites have, in a few cases, been chosen which have different local conditions but are separated by distances small compared to the distance to the source.

2) Where possible, instruments have been placed so as to resolve the highest frequencies of interest. Also the design has been determined by the expected hypocentral depth and fault length of the potential earthquake.

Strike-Slip Fault Array

A hypothetical strike-slip fault and the array proposed to study the source mechanisms of an event on it are shown in Fig. 3.1. Although particular details of the array will vary from site to site, the characteristic dimensions and features are indicated.

In order to minimize local site and propagation path effects, the line of recording stations parallel to the fault has been placed out of the zone of crushed fault gouge on the fault itself, but as close to the fault as deemed possible. The purpose of the lines of stations perpendicular to the fault is to measure the wave decay away from the fault up to a distance comparable with the fault depth, and to aid in the relative location of any "multiple events" occurring in the main shock rupture. There are a few especially long perpendicular lines proposed to study wave propagation effects.

Most of the lines perpendicular to the fault occur on only one side because it is anticipated that radiation of events on such a fault will be symmetric about the fault strike. However, in order to estimate the effect of the local site conditions and propagation path, a few lines of stations extending across the fault have been indicated. Ideally, stations on opposite sides of the fault located at equal distances from the fault will record similar signals. Some of the stations on the lines which transverse the fault can be placed on the fault itself to find an upper limit of acceleration and to investigate the effect of fault gouge. Also indicated in Fig. 3.1 are a few sites of especially dense concentrations of stations: for example, 3-4 stations separated by 50 to 500 m. These subarrays would be used to check the coherency of higher frequency waves and to provide an estimate of the local site effects. It is recommended that the stations in these subarrays be operated in a master-slave mode to ensure a common time base.

Subduction and Dip-Slip Fault Arrays

It is proposed to study two types of faults: 1) the major offshore faults such as those found off the coast of Japan, western South America and the Aleutians and 2) the on-shore dip-slip faults such as those found in the Transverse ranges of Southern California and the Basin and Range Province of the Himalayas. The motivation for studying the latter fault type is to resolve some of the controversies which have arisen from the study of San Fernando earthquake records.

Off-shore Subduction Fault: A hypothetical off-shore subduction fault and a proposed array are shown in Fig. 3.2. Here the instrument spacing is dictated by the focal depth of damaging shallow events. Topography usually permits only a narrow and long array which may extend to more than 500 km. To capture the source characteristics of a large propagating rupture is of prime interest. If topography permits, one or two extended arms of this array may be installed perpendicular to the fault to study the decay of strong motion away from the rupture.

On-shore Dip-Slip Fault: A hypothetical fault of this type and its proposed array are shown in Fig. 3.3. The instrument placement is chosen to determine if the acceleration on the hanging wall is significantly different from that on the foot wall, and if there is significantly higher acceleration along the strike direction or along the direction of the propagating rupture of the fault. Faults of this type usually bring basin sediments in direct contact with basement rocks. An intensified station cluster (Fig. 3.3) may be set up to study the detailed effects of this transition on strong ground motion.

Path Effects Studies

One of the most important problems facing earthquake engineers is to determine the characteristics of the seismic waves generating strong ground motion for a given earthquake source. The question may be resolved for a particular site by a direct wave number analysis of data from the local laboratory type array proposed elsewhere in this report. Twenty to thirty stations spread over an area with diameter 1~2 km will be sufficient to resolve the type of incident waves and incidence angles for the frequency range of engineering interest.

The results from the Local Laboratory Array, however, may not be typical and may be difficult to apply to other sites and other sources. To find any systematic dependence of the characteristics of strong motion on the wave path, it is necessary to have an array of stations with greater areal coverage than that of a local effects laboratory array.

The problems which must be addressed are:

1) To find the wave characteristics of strong motion as a function of distance and frequency for a relatively uniform crust, for the distance range 0 to 100 km and the frequency range $0.1 < f < 30$ Hz. For example, it may be desired to study systematically the effect of an extensive low-velocity waveguide which may cause a dominance of surface waves for certain ranges of frequency and distance.

2) To find effects of relatively simple types of lateral heterogeneity on strong motion. Examples of heterogeneities are:

    a) boundaries of sedimentary basins for wave paths with various incidence angles,

    b) contacts of different upper crustal materials such as the boundary of the Gabilan range and Franciscan formation,

    c) roots of mountains such as the Andes,

    d) effects of deep waveguides such as observed in Japan and Romania for deep and intermediate earthquakes.

3) To study the effects of more complex heterogeneity, it will be necessary to compile a library of empirical impulse responses for a large number of source-receiver combinations. Such a library may be used for the synthesis of strong motion by convolving the source function with the empirical impulse response. It will be hypothesized that the impulse response representing the path-effect may be common for strong and weak motions. This assumption can be tested when necessary data become available.

In order to solve the above problems, a large amount of data from regions of various geological and topographical conditions is needed.

Herein, as a fixed permanent array for the path effects study, it is proposed to add extension legs from the source mechanism arrays (Fig. 3.1), some of them preferably connecting to the laboratory arrays designed to study local effects. These arrays will generally be linear arrays of about 10 accelerographs distributed over a distance of about 100 km. Accelerograph specifications for these arrays are the same as for the mobile array described below.

It would perhaps be difficult to acquire data necessary for a more complete study of path effects in the near future by a permanent array fixed in an area. However, necessary data may be acquired from a mobile array laboratory staffed permanently with technicians and ready for deployment in the aftershock area of earthquakes with magnitude greater than 7.

3.5 MOBILE ARRAY LABORATORY

Since the earthquakes to be studied by the mobile array may occur in an area without any local seismic network, the mobile array must have the capability of locating aftershocks with an accuracy of about 1 km. Since large aftershocks will supply valuable information on the source process, the mobile array should have the capability of source study as described in a previous section. Both capabilities are provided by the digital recorders proposed here.

It is anticipated that the extent of the aftershock area for a target earthquake would be around 100 km. For aftershock location and source study, three rows of seismographs spaced at about 10 km intervals covering the aftershock area will be required.

For a systematic study of path effects described earlier, suitable array configurations must be selected for each specific geologic and topographic condition. An aftershock zone of length about 100 km will require about 50 stations to collect data for aftershock location, source study and various path effects. The deployment and operation of an array of this magnitude will require several teams of experienced technicians.

There is no clear boundary separating path effects from local effects. In fact, instrument layout for the study of path effects must, in general, merge into arrays designed to study local effects so as to maintain observational continuity. The concept of the Mobile Array Laboratory should be equally effective as a supplement for local effects arrays when and if the situation calls for such a deployment.

The seismograph specifications for the Mobile Array Laboratory are similar to those for the permanent arrays. They are summarized in the following section.

3.6 INSTRUMENT CHARACTERISTICS

It is deemed desirable that the individual stations of the arrays described herein have a bandwidth from 0.1 to 30 Hz and a dynamic range (using gain ranging) of 10^6. The sensors should be capable of recording three components of motion linearly over this bandwidth with a maximum acceleration of 2g. (With simple modifications, a few instruments could probably be used to record as high as 5g.) Internal clocks should have a drift rate not exceeding 10^{-7}. These clocks must be able to be re-set from an external, portable master clock so that the precise relative timing can be obtained periodically and especially immediately after a large event. The sample rate should be 100 Hz to allow for reliable recording of 30 Hz signals after anti-aliasing filtering. It is suggested that pre-whitening filtering be investigated. Recording time should be as long as a cassette tape would last, with 45 minutes as a minimum recording time.

The recorders should have "smart" triggers and pre-event memories of 2 sec. The trigger threshold and full-scale range should be easily adjustable to allow for studies of such things as aftershock sequences and refraction profiling. One of the primary goals of the arrays is to separate source effects from propagation path and local site effects. If the gain of all the stations in an array could be increased substantially and the trigger level lowered, teleseisms could be observed across the array as a means of estimating differences in local site effects. Routine, convincing instrument calibrations are necessary. A filter with adjustable frequency band may be needed in the trigger channel to respond to different sites with different signal and noise conditions.

3.7 ANTICIPATED RESULTS

Permanent Source Mechanism and Path Effects Arrays

The strong-motion records collected by permanent arrays will answer a number of questions of great importance in earthquake engineering and strong-motion seismology. In particular, the following results are expected:

1) Description of the effects of the type of fault or fault mechanism (strike-slip, thrust, normal) on strong motion.

2) Spatial variation of strong motion in the near source region (20 km from fault) including radiation pattern and regions in which strong motion may be intensified by constructive interference of waves emanating from a moving rupture front.

3) Classification of the rupture process as unilateral or bilateral.

4) Measurement of rupture velocity which can be used in kinematic fault models and in the testing of rupture physics models.

5) Location of multiple events or events in which abrupt changes in rupture velocity and slip velocity occur. These portions of the fault may generate most of the high frequency components of strong motion. It will be possible to correlate their location with the surficial and subsurface geology permitting generalization of the results to noninstrumented regions.

6) The records obtained in the near source region and on the legs of the permanent arrays will permit construction of reliable spatial attenuation functions which may depend on frequency and earthquake magnitude.

7) Comparison of recordings at a station for earthquakes of different magnitudes will be used to establish the degree of nonlinearity.

8) Permanent arrays will provide input information for the local effects arrays.

Mobile Arrays

The strong-motion data obtained by mobile arrays should provide needed information in the following areas:

1) Evaluation of the wave content of ground motion, i.e. relative importance of body and surface waves as a function of distance and frequency.

2) Effects of different types of surficial and subsurface geological structures on ground motion including the effects of lateral changes in structure.

3) Source information for earthquakes of lower magnitudes and for regions in which permanent arrays are impractical.

4) Evaluation of empirical Greens or impulse response functions which may be used to synthesize ground motion for larger earthquakes at particular sites.

In general, both the permanent and mobile types of arrays will provide empirical information that can be used directly in engineering design. Furthermore, detailed data so systematically gathered may be used to validate existing analytical models as well as guide the development of more complete models that govern the seismic source and propagation path effects on strong ground motions. The ultimate goal, of course, is to develop an ability to predict strong earthquake ground motion.